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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
30 Sep 2009

2. REPORT TYPE
REPRINT

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
SOURCE AND PATH CALIBRATION IN REGIONS OF POOR CRUSTAL PROPAGATION USING TEMPORARY, LARGE-APERTURE, HIGH-RESOLUTION SEISMIC ARRAYS

5a. CONTRACT NUMBER
FA8718-09-C-0004

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62601F

6. AUTHOR(S)
John L. Nabelek1, Jochen Braunmiller1, and W. Scott Phillips2

5d. PROJECT NUMBER
1010

5e. TASK NUMBER
SM

5f. WORK UNIT NUMBER
A1

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Oregon State University
312 Kerr Admin. Bldg
Corvallis, OR 97331

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
29 Randolph Road
Hanscom AFB, MA 01731-3010

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RVBYE

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RV-HA-TR-2009-1082

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited.

Oregon State University1 and Los Alamos National Laboratory2

13. SUPPLEMENTARY NOTES
Reprinted from: Proceedings of the 2009 Monitoring Research Review – Ground-Based Nuclear Explosion Monitoring Technologies, 21 – 23 September 2009, Tucson, AZ, Volume I pp 158 - 165.

14. ABSTRACT

Broadband seismic data acquired during the Hi-CLIMB field experiment are used to study seismic events and path propagation in the Nepal Himalaya and south-central Tibetan Plateau. Similarities in regional propagation between Tibet and Iran motivate this new study. The 2002–2005 Hi-CLIMB experiment consisted of 233 stations distributed along a dense 800 km linear north-south array extending from the Himalayan foreland into the central Tibetan Plateau. The main array was flanked by a 350 km x 350 km sub-array in southern Tibet and central and eastern Nepal. Our dataset provides an opportunity to obtain seismic event locations for ground truth (GT) evaluation, with emphasis on depth, to determine source parameters, and to study distance evolution of seismic coda for yield estimation in low Q regions. Event detection and preliminary automatic location analysis show tens of thousands, otherwise undetected, local seismic events. We will obtain high-quality event locations from manual *P*- and *S*-wave picks by joint inversion for location and 2D and 3D velocity structure. We will also perform relative locations to resolve spatial relations of several highly active event clusters. Besides GT-compatibility, high-quality locations are essential for the source parameter and coda evolution portions of the study. We will perform moment tensor inversions in a wide magnitude range ($1.5 \leq Mw \leq 6$), paying particular attention to event depth and size. Full waveform moment-tensor depth is important for validating traveltime-derived depth; seismic moment calibrates spectral coda levels and local and regional magnitudes. The dense station spacing of the Hi-CLIMB array is unique for any highly attenuating crustal path region, permitting fine-scale analysis of decay properties for multiple coda types, which is a globally important, unresolved issue in monitoring research. The GT-level locations and moment tensor depths will contribute to Seismic Location Baseline Model (SLBM) tomographic efforts, allow evaluation of depth mislocation for crustal models, and enhance model accuracy throughout central and southern Asia.

15. SUBJECT TERMS
Ground Truth, Moment tensors, Seismic coda, Tibet

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Robert J. Raistrick
a. REPORT	b. ABSTRACT	c. THIS PAGE	SAR	8	19b. TELEPHONE NUMBER *(include area code)*
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SOURCE AND PATH CALIBRATION IN REGIONS OF POOR CRUSTAL PROPAGATION USING TEMPORARY, LARGE-APERTURE, HIGH-RESOLUTION SEISMIC ARRAYS

John L. Nabelek[1], Jochen Braunmiller[1], and W. Scott Phillips[2]

Oregon State University[1] and Los Alamos National Laboratory[2]

Sponsored by the Air Force Research Laboratory

Sponsored by the National Nuclear Security Administration

Award No. FA8718-09-C-004[1] and DE-AC52-06NA25396[2]
Proposal No. BAA09-28

ABSTRACT

Broadband seismic data acquired during the Hi-CLIMB field experiment are used to study seismic events and path propagation in the Nepal Himalaya and south-central Tibetan Plateau. Similarities in regional propagation between Tibet and Iran motivate this new study. The 2002–2005 Hi-CLIMB experiment consisted of 233 stations distributed along a dense 800 km linear north-south array extending from the Himalayan foreland into the central Tibetan Plateau. The main array was flanked by a 350 km x 350 km sub-array in southern Tibet and central and eastern Nepal. Our dataset provides an opportunity to obtain seismic event locations for ground truth (GT) evaluation, with emphasis on depth, to determine source parameters, and to study distance evolution of seismic coda for yield estimation in low Q regions. Event detection and preliminary automatic location analysis show tens of thousands, otherwise undetected, local seismic events. We will obtain high-quality event locations from manual *P*- and *S*-wave picks by joint inversion for location and 2D and 3D velocity structure. We will also perform relative locations to resolve spatial relations of several highly active event clusters. Besides GT-compatibility, high-quality locations are essential for the source parameter and coda evolution portions of the study. We will perform moment tensor inversions in a wide magnitude range ($1.5 \leq M_w \leq 6$), paying particular attention to event depth and size. Full waveform moment-tensor depth is important for validating traveltime-derived depth; seismic moment calibrates spectral coda levels and local and regional magnitudes. The dense station spacing of the Hi-CLIMB array is unique for any highly attenuating crustal path region, permitting fine-scale analysis of decay properties for multiple coda types, which is a globally important, unresolved issue in monitoring research. The GT-level locations and moment tensor depths will contribute to Seismic Location Baseline Model (SLBM) tomographic efforts, allow evaluation of depth mislocation for crustal models, and enhance model accuracy throughout central and southern Asia.

OBJECTIVES

The broadband dataset from the 2002–2005 Hi-CLIMB seismic array in the Himalayan-Tibetan collision zone is unique in its large aperture and dense station spacing. The purpose of our research is to improve source and path calibration in regions of poor crustal propagation to enhance the monitoring community's capabilities to estimate magnitude and yield of future nuclear tests in low Q and highly scattering environments. We have three closely linked objectives. The first is to obtain high-precision ground-truth seismic event hypocenters. The second is to provide seismic moment and independent depth estimates from waveform modeling of local and regional earthquakes. And the third is to determine the distance evolution of seismic coda, utilizing the quasi-continuous control offered by the dense, laterally large network (paying emphasis on mantle coda), important for low Q areas.

RESEARCH ACCOMPLISHED

Data

The Hi-CLIMB broadband seismic experiment (Nabelek et al., 2005; 2009) consisted of 233 sites in Nepal and the south-central Tibetan Plateau (Figure 1). The network operated from 2002 through 2005 and each site was occupied for 12 to 20 months. The network consisted of an 800-km long north-south array covering the India-Eurasia collision zone from the Ganges foreland across the Higher Himalayas into the Tibetan Plateau. Station spacing was 3-4 km in the south and about 8 km north of the Yarlung-Tsangpo suture. Complementary lateral deployments, with 30 to 40 km station spacing, in central and eastern Nepal and southern Tibet improve earthquake location capabilities and provide wave propagation control for the transition from the foreland into the plateau. All data were recorded continuously at 50 sps. The Hi-CLIMB data provide an opportunity to determine locations, source parameters and coda distance evolution of small sized seismic events at unprecedented accuracy in central Asia.

Additional broadband data are available from the earlier HIMNT experiment in eastern Nepal and southern Tibet (e.g., Sheehan et al., 2004; Monsalve et al., 2005; de la Torre et al., 2006) and from the five-station Program for the Array Seismic Studies of the Continental Lithosphere (PASSCAL) Bhutan pilot experiment (Velasco et al., 2003). HIMNT occupied a similar area as our eastern-Nepal/southern-Tibet subnet (Figure 1), but with fewer stations and shorter operation times from late 2001 into 2002.

Figure 1 shows the large spatial extent and high station density of the Hi-CLIMB project. Coupled with long recording durations, this results in a much-improved coverage of this large, complicated tectonic region. We observe a very high seismicity rate with about 1000 events per week (Figure 2) compared to fewer than 1700 events for an 18-month period during HIMNT (e.g., de la Torre et al., 2006) that were mainly located in Nepal. As an example, Figure 3 shows preliminary locations from central and southern Tibet, largely in areas not covered by any previous experiments or permanent networks.

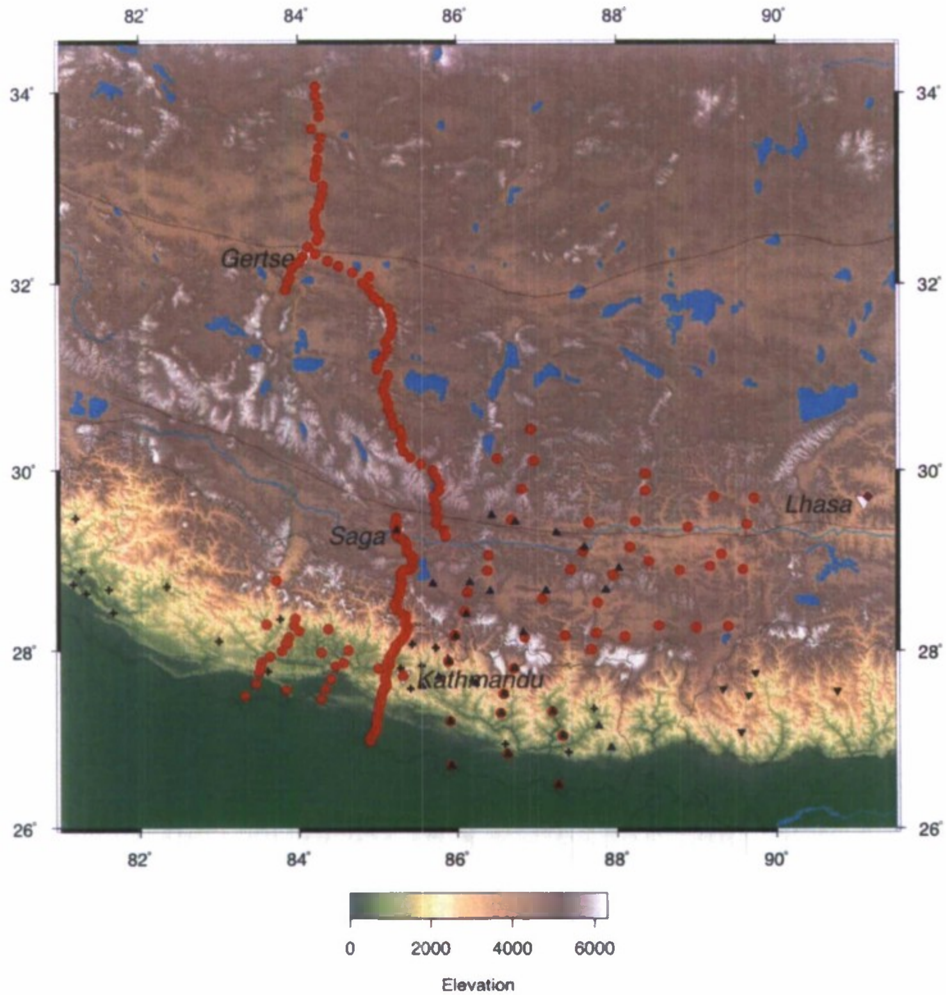

Figure 1. Hi-CLIMB (red circles), HIMNT (blue upright triangles), and Bhutan (black inverted triangles) broadband temporary stations and Nepalese National Seismic Network (crosses). During the first 20 months of Hi-CLIMB (Nepal and South Tibet), 75 broadband instruments were available while during the second 15 months (South and Central Tibet), 111 instruments were available. Altogether, 233 sites were occupied.

Event Detection and Preliminary Location

The entire Hi-CLIMB waveform database (1.4 TB) has been organized using the Antelope software developed by Boulder Real Time Technologies (BRTT). The package includes modules for automatic detection and arrival time picking, event-arrival association and event location. Preliminary analysis of event detections reveals about a thousand legitimate event detections per week (Figure 2). For the second half of the experiment, we located over 60,000 events of magnitude greater than 0. This is more than 300 times the number of events listed in the United States Geological Survey (USGS) Preliminary Determination of Epicenters (PDE) catalog for the same region and period. For some events, the PDE locations also show a mismatch of up to 50 km.

We developed several modules to weed out spurious detections as well as erroneous phase and event associations to automate data management. Figure 3 shows the resulting fully automatic preliminary event locations for a 15-month time period for events with at least 15 *P* and *S* arrivals corresponding roughly to M≥2, which is a relevant cut-off for monitoring purposes. Most shallow seismicity north of the Yarlung-Tsangpo suture (north of 29.5°N) is in an area

not investigated by most other experiments. These locations, although fully automatic, utilize many S-arrivals and correlate with geologic structures seen in satellite imagery suggesting they are already quite accurate.

We will locate as many events as possible, but will focus on locating selected events at the GT20 level and better with careful consideration of depth and absolute location uncertainties as required. We plan to arrive at accurate locations through a succession of location steps eliminating events that do not pass more strict requirements and resulting in a subset of refined locations. An important part of this work will include improving crustal structure models.

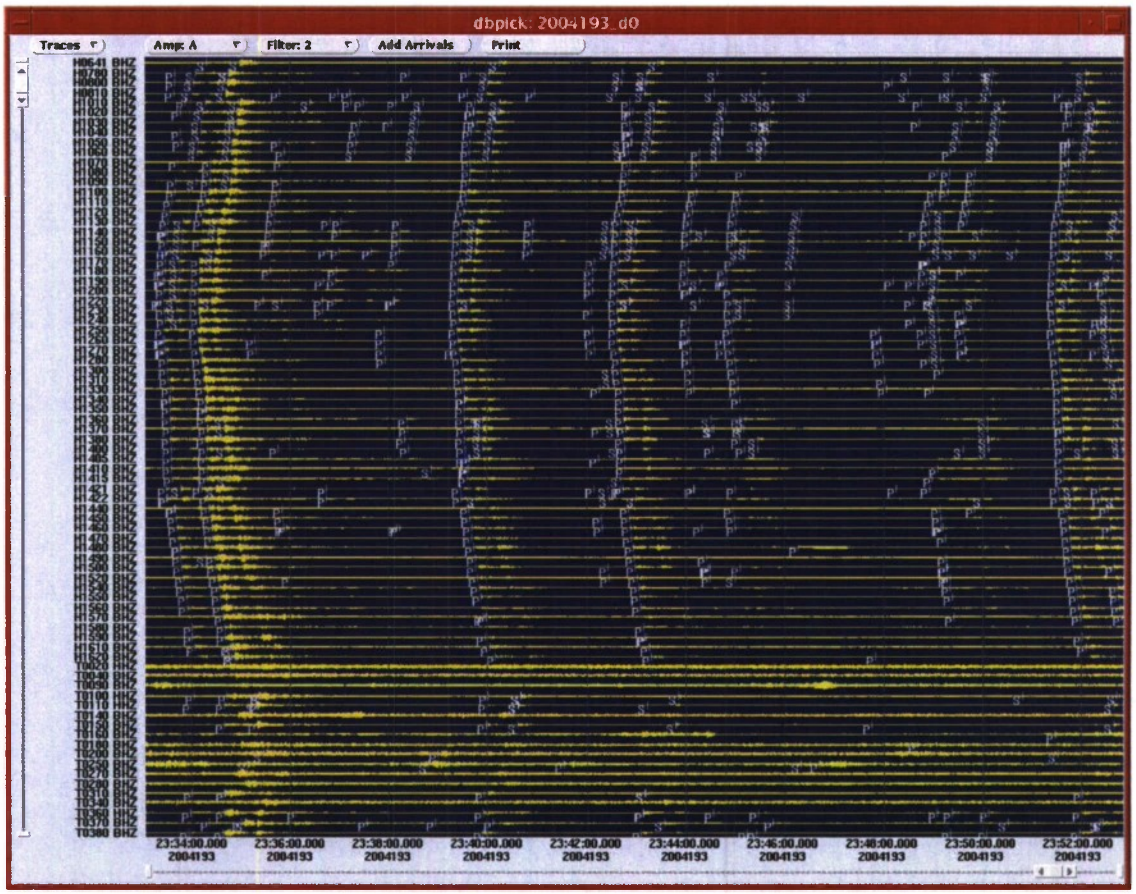

Figure 2. Event detection for a 20-minute Hi-CLIMB data window (Julian day 193, 2004, start 23:33 UTC). *P*- and *S*-phase association has been performed and four stronger local events were recorded across the array and many smaller events at specific station groups only.

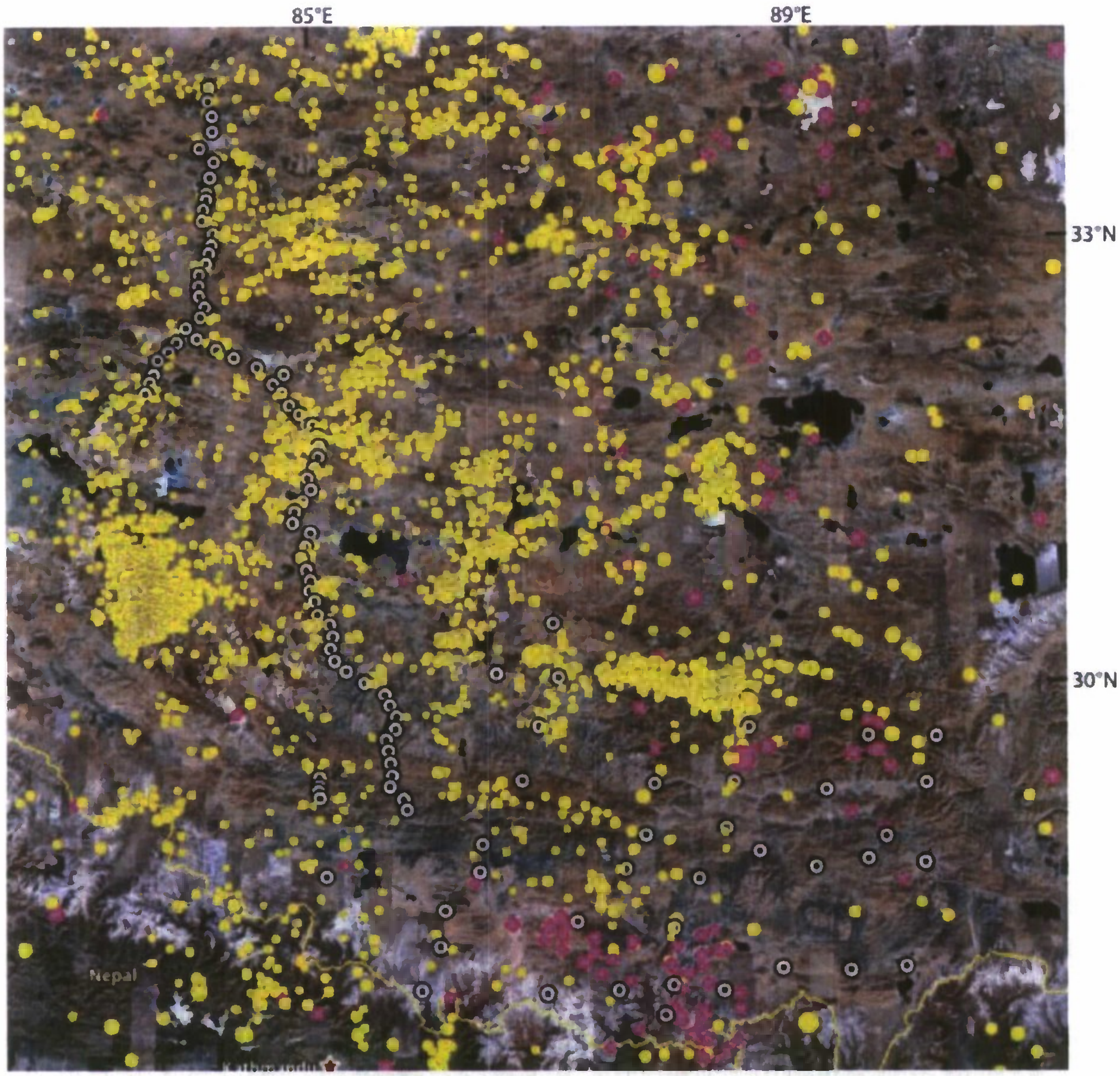

Figure 3. Preliminary epicenter map (colored circles) for 15-month period covering the second half of the Hi-CLIMB experiment (recording stations black circles). Over 60,000 events have been located. We plot 11,000 events with at least 15 *P* and *S* arrivals. Yellow: depth ≤ 60 km (crustal events) and purple: depth > 60 km (potential upper mantle events). The numerous shallow events north of the Yarlung-Tsangpo suture (>29°N) have not been covered by previous experiments.

Source Parameters from Regional Moment Tensor Inversion

Regional moment tensor studies in the Himalayan-Tibetan region have been performed (Burtin, 2005; Burtin et al., 2005; Baur, 2007) for selected larger earthquakes using the full waveform inversion code developed by Nabelek and Xia (1995). Results obtained thus far are summarized in Figure 4. Burtin (2005) tested analysis feasibility with permanent far-regional stations. Deriving station specific velocity models, he analyzed 29 M_w>4.5 events that occurred from 1988 to 2000 within 1000 km of closest station LSA (Lhasa, Figure 1) along the southern boundary of the Tibetan Plateau. Long paths require analysis at long periods (T≥33 s), which limits parameter resolution and sets a high analysis threshold. The Hi-CLIMB data allow analysis of much smaller M_w≈3.5 events with near-regional seismograms at periods of T≥15–20 s (Baur, 2007); so far, we have obtained more than 100 moment

tensors (Figure 4). The high data quality and redundancy allow parameter resolution tests for size, depth, and moment tensor. Preliminary analysis suggests a depth resolution for shallow crustal events on the order of ±5 km and an estimated M_w uncertainty of ±0.1–0.2 units with currently used velocity models and event locations.

Quality event locations and improved structural models that are being developed as part of the GT effort will be important to increase accuracy and resolution of the source parameters. The improved models will also be used to analyze smaller events near M=3 at near-regional distances and to model larger-event waveforms reliably for distances up to 1000 km at short periods near T=10 s. Selected smaller events near the dense array will be analyzed in conjunction with the GT location effort (e.g., to obtain independent depth estimates) and requirements of the coda wave modeling (e.g., to provide seismic moment over a range of event sizes for calibration of absolute spectral levels from coda to bands approaching those used for yield estimation).

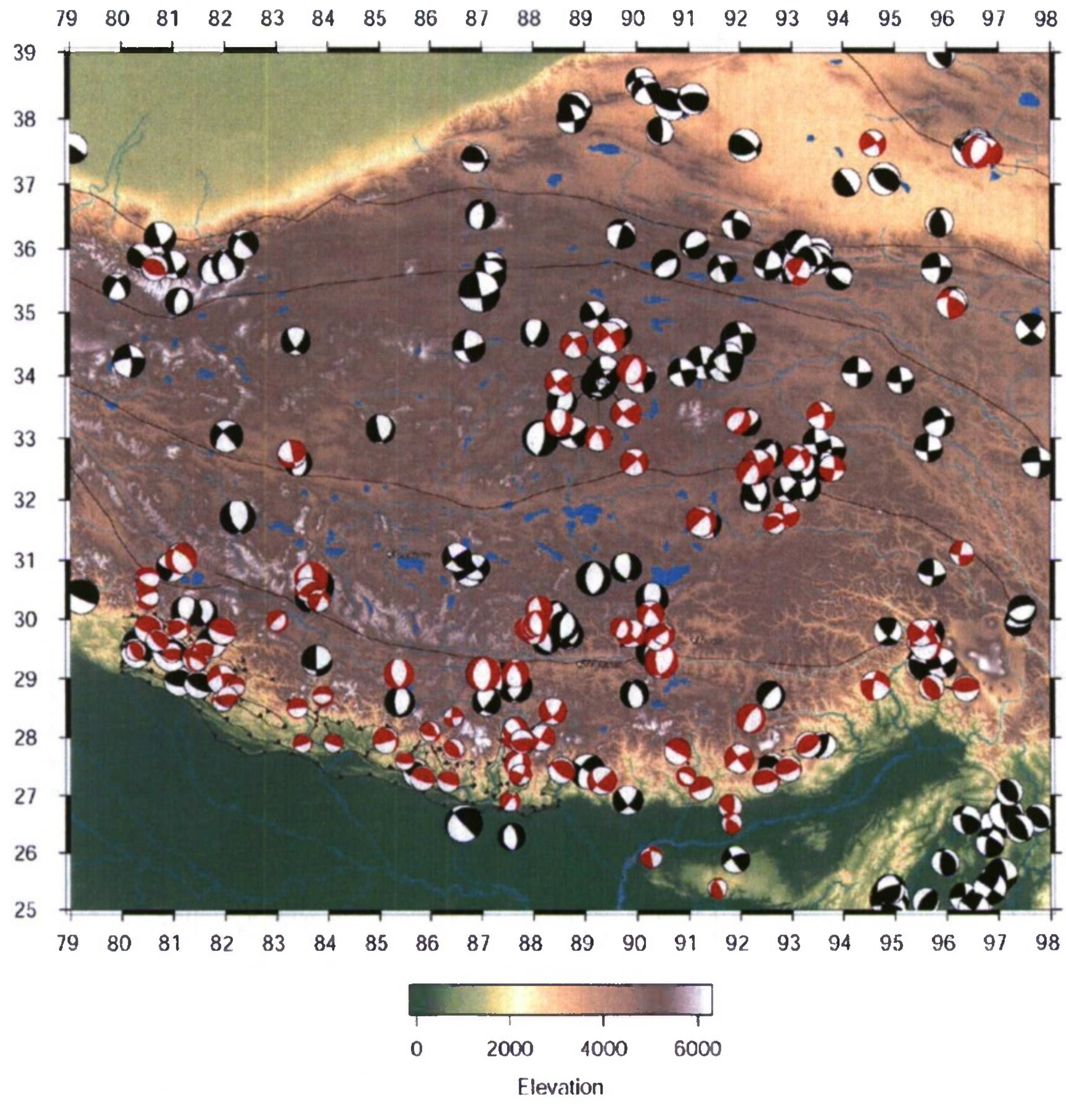

Figure 4. Regional moment tensors (red: Burtin, 2005: Baur, 2007) and Global Harvard centroid moment tensors (CMTs) (black). We completed analysis of 150+ largest events in the Tibet region using all high-quality waveforms. The Hi-CLIMB set of 130+ solutions contains events as small as M_w=3.5. 166 CMT solutions, mainly M_w>5.0, exist for 1976–2005. In southern Tibet and Nepal our efforts substantially expand the moment-tensor catalog.

Propagation Models for Multiple Coda Types

Analysis of coda waves provides stable, high precision amplitude measurements for magnitude and yield estimation. The averaging nature of the scattered waves that form the coda reduces the effects of source mechanism and path, allowing measurement stability from one station that would only be obtainable from a dense array for direct waves.

Coda measurements incorporate corrections to account for distance dependent amplitude decay under the usual assumption that one phase (surface waves, *Lg*, *Sn*, or *P*) dominates the coda. However regions of extremely low crustal Q or *Lg* phase blockage support diverse types of coda even within one frequency band as a result of *Lg* phase stripping exposing mantle coda associated with *Sn* and/or *P*n. Mantle coda are not as well excited as *Lg* coda, but higher Q at depth supports their longer duration such that low crustal Q allows observation of mantle coda at shorter distances. Figure 5 shows coda evolving from *Lg* to *Sn* over regional distances for station LSA in Tibet.

The length and station density of the Hi-CLIMB array offers a unique opportunity to study the evolution of multiple coda types and develop new models and parameters to enable their use. Specifically, we are interested in: 1) precise determination of short distance path parameters for *Lg* coda from amplitude differences, a technique requiring high station density, which is unavailable across most of Asia, 2) development of path models and relative transfer functions for multiple coda types (e.g., Phillips et al., 2008); and 3) development of strategies for integrating measurements for different coda types to obtain absolute source spectra for M_w and yield estimation. In regions of extremely low crustal Q, like Tibet and Iran, identification of dominant coda type at a given distance and its decay are crucial for accurate size estimation.

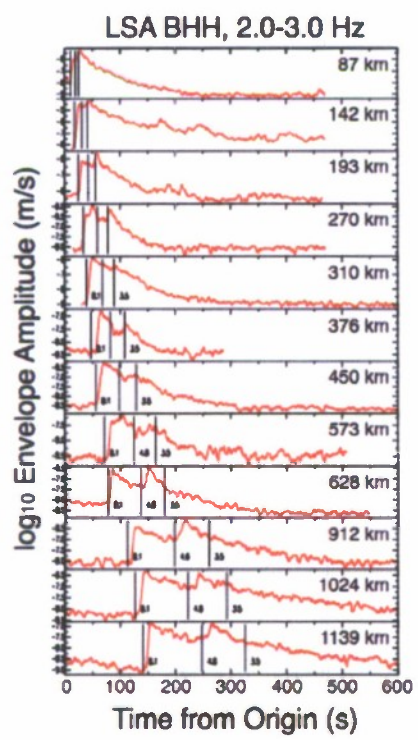

Figure 5. Evolution of 2-3 Hz coda from *Lg* to *Sn* in Tibet for events recorded at LSA. Distances are noted to the right of each envelope. Group velocities of 8.1, 4.6 and 3.5 km/s, representing *Pn*, *Sn*, and *Lg*, respectively, are marked.

CONCLUSIONS AND RECOMMENDATIONS

The Hi-CLIMB broadband seismic dataset provides the opportunity for ground truth location and source parameter determination and the study of distance evolution of seismic coda in central Asia. The dataset reveals an abundance of seismic events that are not included in any other catalog. Initial waveform modeling efforts resulted in a 150+ event moment tensor database. The GT level locations and moment tensor depths will contribute to SLBM tomographic efforts, allow evaluation of depth for crustal models, and enhance model accuracy throughout central and southern Asia and, in general, will contribute to the National Nuclear Security Administration (NNSA) Knowledge Base. The high station density of the network allows a detailed study of seismic coda to gain understanding of its distance evolution in a region of low crustal Q; results will probably not transport directly from Tibet to other regions of low crustal Q, like Iran, but will lead to development of strategies for coda analysis that are globally useful.

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